CLIMATIC VARIATIONS

THEIR EXTENT AND CAUSES

BY

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UNIVERSITY, GLASGOW.

MÉXICO.

IMPRENTA Y FOTOTIPÍA DE LA SECRETARÍA DE FOMENTO

Callejón de Betlemitas número 8.

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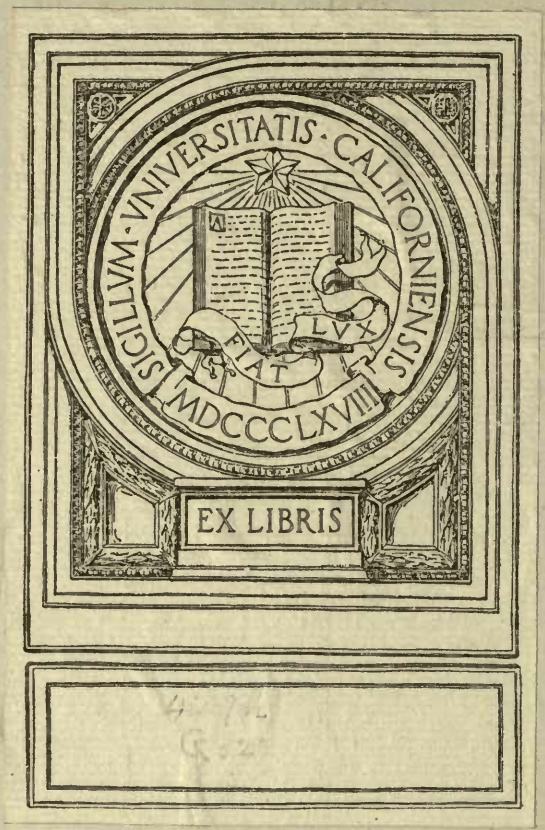
1906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BY PROFESSOR
J. W. GREGORY F. R. S. UNIVERSITY, GLASGOW.

I.—Introduction.

The past variation of climate is an attractive study, as it controls so many questions in geology, geography and meteorology. But subject is of especial difficulty, as it deals with the action of complex chemical and physical processes working under conditions and on materials, which can be estimated only by the freest speculation. The question may be approached a priori by consideration of the evolution of the atmosphere, as suggested by general chemical probabilities; or we may determine from the sedimentary rocks the strength and nature of the geographical agencies that formed them; or we may examine the indirect evidence given by fossils as to the climates under which they lived. The fact of marked local variations in climate is abundantly proved; and it will probably be equally agreed, that there is no evidence known to the geologist of any progressive refrigeration of the earth. The idea of the secular cooling of the earth is deeply impressed on our terminology; but geological principles are independent of the theory. The terms suggested by it may always be retained from their historic interest and convenience, as we still speak of the rising of the sun. Responsibility for the belief in the secular cooling of the earth rests with the astronomers and physicists, from whom geologists have accepted it.

Local variations in climates are abundantly established by the former glaciation of temperate regions, the once greater extension of glaciers in tropical regions, and the frequent growth

of reef-building corals outside their present geographical limits. But we need not unnecessarily increase the difficulties of the problem by accepting the world-wide range of great climatic changes without convincing evidence. Dr. Ekholm takes as the starting point of his valuable paper, the ground that "the inqui-"ries of modern geology unanimously indicate that all great "climatic changes have occurred simultaneously on the whole "earth."[1]

But geological opinion is by no means unanimous on this question; and the major climatic variations were world-wide in their influence. The amplest evidence in support of the view that a colder climate was once universal is supplied by the Pleistocene glaciations; and it is certain that at one part or another of the Pleistoncene period, the glaciers of many distant parts of the world were much larger, and that wide areas in the north temperate zones were overwhelmed by glacial conditions. But there appears to be a steadily growing opinion that the glaciers of the different glacial centres did not attain their greatest development at the same time. Thus the glaciation of Greenland is now at its maximum; at an earlier period of the Pleistocene, Labrador was covered by an ice-sheet, which dwindled as that of Greenland developed; and the glaciation of the Canadian Rocky Mountains was probably still earlier than that of Labrador. Similarly in Europe, the conditions of preservation and general aspect of the glacial deposits suggest that the culmination of the Norwegian glaciation was somewhat later than that of the British Isles.

II.—The General Uniformity of Climates in the Past.

The first striking fact in the geological history of climate is that the present climate of the world has been maintained since the date of the earliest, unaltered, sedimentary deposits. The oldest sandstones of the Scotch Hihglands and the English Longmynds, show that in pre-Cambrian times the winds had the same strength, the rain drops were of the same size, and they

1 Dr. Nils Ekholm. "On the Variations of the Climate of the Geological and Historical Past and their Causes." Q. J. R. Met. Soc. XXVII, 1901, p. 3.

fell with the same force as at the present day. The evidence of palaeontology proves that the climatic zones of the earth have been concentric with the poles as far back as its records go; the salts deposited by the evaporation of early Palaeozic lagoons show that the oldest seas contained the same materials in solution as the modern oceans; and glaciations have recurred in Arctic, and, under special geographical conditions, also in temperate regions, at various periods throughout geological time.

The mean climate of the world has been fairly constant; though there have been local variations, which have led to the development of glaciers in regions now ice-free, at various parts of the geological scale. That there has been no progressive chilling of the earth since the date of the oldest known sedimentary rocks, is shown by their lithological characters, and by the recurrence of glacial deposits, some of which were laid down at low levels, at intervals throughout geological time. Thus remnants of a series of glacial deposits, which are probably pre-Cambrian, occur in a series of localities around the Arctic Zone;[1] fragments of this early, circum-Arctic glacial chain occur in the North of Norway, as described by Reusch and Strahan;[2] in Spitsbergen;[3] as some boulder beds, the descriptions of which are suggestive of glacial formation, on the Coppermine River, and in Labrador, where however, according to A. P. Low, they may be Cambrian; and finally on the northern coasts of Siberia, near the estuary of the Lena. The Cambrian System contains an extensive series of glacial deposits, discovered by Mr. Howchin[4] running north and south through South Australia, between the latitudes of 32° and 35° S.; and as these Cambrian tilk are interstratified with marine rocks, they were probably formed about sea level.

The next proved glacial period is the Upper Carboniferous

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1 W. Gregory. Quart. Journ. Geol. Soc. Vol. LIII, 1897, p. 155.

2 A. Strahan. "The Raised Beaches and Glacial Deposits of Varanger Fiord." Ibid. Vol. LIII, 1897, pp. 147-153.

3 The Pre-Cambrian Glacial bed in Spitsbergen was referred to by Nordenskjold. I accidently rediscovered it at Fox Point on Bell Sound in 1896, and sketched the best exposed section; Quart. Journ. Geol. Soc. Vol. LIV, 1898, p. 216.

4 Brief Reference to these Cambrian Glacial Deposits is given in Mr. W. Howchin's paper "The Geology of the Mount Lofty Ranges." Pt. I., Trans. R. Soc. S. Austral., Vol. XXVIII, 1904, pp. 259, 278 and pl. XLIII.

and perhaps Permian, as proved by the glacial deposits of India, South Africa, Australia, and South America. They vere originally assigned, in Africa and Australia, to the Trias, and subsequently to the Permian; and the Permian age of the South Africa glacial deposits still asserted by some geologists. But according to Mr. Seward[1] the glacial deposits at Vereniging—which according to one theory are redeposited glacial material and would therefore be the latest of the South African glacial beds,—are Upper Carboniferous, and that is the age of the best known and most extensive of the glacial deposits of south-eastern Australia. The Upper Cretaceous has some evidence of glaciation in the Northern Hemisphere; for the ocurrence of drift ice is the most probable explanation of the boulders found in the British chalk; and Professor Garwood found a glaciated pebble on Bunting Bluff in Spitsbergen, in some conglomerates which are upper Cretaceous, or Lower Cainozoic.[2] With the exception of such scraps of evidence there is no convincing proof of low level glacial action until we reach the Pleistocene.

III.—Exaggerated Estimates of Climatic Changes.

The range of climatic variations in the past has been often greatly exaggerated, thereby leading to the apparent necessity for revolutionary changes in former meteorological conditions. But the climatic changes we have to explain, appear to have been either local in area or moderate in degree.

The opinion, that there have been fundamental changes in climate, is based mainly upon the evidence of former glaciations, and on the supposed existence of tropical climates in the Arctic regions. That tropical or sub-tropical conditions once prevailed within the Arctic circle is affirmed on the reported occurrence there of fossil coral reefs and tropical vegetation. I have previously quoted evidence to show that this view is greatly exaggerated.[3] One notice of that paper described its views as "très hardie," but I am not award of any refutation

1 A. C. Seward. "Fossil Floras of Cape Colony." Annals S. Africa Museum, Vol. IV, Pt. I, 1903, p. 101.

2. Quart. Journ. Geol. Soc. Vol. LIV, 1898, p. 217.

3 Some Problems of Artic Geology. II. Former Arctic Climates.

of its conclusions. The idea of the former tropical condition of Greenland is still confidently asserted. Thus Dr. Ekholm[1] refers to the nearly tropical climate that prevailed in the Arctic regions during the Cretaceous age, when he estimates that the mean temperature was 36° F. higher than during the Pleistocene. But so far as I know the evidence, there is no proof that the Arctic regions ever had a subtropical or even a warm temperate climate.

(a) *The Evidence of Fossil Corals.*

The Arctic Ocean has been described as having been a coral sea in Silurian and Carboniferous times. This view led to Blandet's suggestion—well known by its advocacy by Sir John Murray—that in Palaeozoic times light and heat were equally distributed throughout the world; and also to the theories that the heat from the sun is diminishing owing to the smaller size of the sun, as suggested by Helmholtz, or to its lower intensity, as advocated by Dubois. But the fossil faunas of the Arctic seas all show the dwarfing effect of unfavourable conditions, when compared to the contemporary faunas in the seas to the south.

Corals of reef building genera have lived in the Arctic regions; but I have seen no Arctic specimens larger than nodules, which could have grown ir a cool sea. The asserted existence of Arctic coral reefs in Silurian times was based on a collection made in Grinnell Land, which is now in the British Museum. But the specimens show nothing more than the growth of small nodular corals, such as may have grown in a temperate sea; Palaeozoic corals have also been found in the Timan-Urals and in the Silurian rocks of theNew Siberian Islands; but in both cases the evidence shows that the coral faunas were stunted in comparison with those of the contemporary seas to the south. Numerous simple and simply branched corals, associated with thick growths of calcareous algae, grow to-day in the northern seas. Dead branches of Lophohelia are so common on one bank in the Christiania Sound (lat. 58° N.) that it has been described as a Pleistocene coral reef. Small nodules of corals, of reef

1 Ekholm. Op. cit. pp. 25, 26.

building genera, such as Plesiastraea, live at present in the cold seas of Southern Australia, far to the south of the region of coral reefs.

Hence I feel justified in repeating the view expresed in 1897, that the evidence of the fossil corals from the Silurian rocks of Greenland Britain shows "that there was almost as great "a difference between the temperature of the sea in the areas "as there is to-day."[1]

The evidence of the fossil corals is supported by that of the Arctic marine faunas of all geological periods. Their most striking characteristics in the past are their characteristics of to-day, and show "that all through geological time the northern "faunas have lived under the blight of Arctic barrenness."[2]

(b) *The Evidence of the Fossil Floras.*

The fossil floras of the Arctic as identified by Herr, have been used as the basis of the attractively sensational theory that Greenland enjoyed a tropical climate in Miocene times and a tropical or sub-tropical climate in Cretaceous times. But the evidence so far adduced appears to be quite insufficient to justify this view. The most characteristically tropical of the plants claimed to occur in Greenland are the palms; but the fossil Arctic palms have now been dismissed as based on erroneous identifications. Much weight has also been attached to some fossil tree-ferns of the genus Dicksonia, from the Cretaceous of Greenland. But the best known living species of that genus is Dicksonia Antarctica, which occurs in southern New Zealand; and Dicksonia also lives on the high "Snowy Plains" of the Victorian Highlands, where it is sometimes buried under snow for four or five months in the year. Hence the existence of fossil treeferns, especially of the genus Dicksonia, would certainly not imply tropical conditions. Heer's identifications have been contemptuously rejected by many later botanists, including Dr. Robert Brown, Dr. Starkie Gardner and Professor Nathorst. Most of Heer's determinations were based upon leaves, which give no

1 Op. Clt., Nature, Vol. LVI, 1897, p. 352.
2 Ibid. p. 352.

data for generic identification. Nor does the existence of leaf beds in the Arctic prove anything more than local geographical changes; for leaves grow with remarkable rapidity and luxuriance within the Arctic circle, under the influence of the continuous day light of summer. That dense foliage grows upon the moraines of Alaska is well known from the photographs, taken upon the Malaspina Glacier, published by I. C. Russell;[1] and in the same district, forests of fir trees growing on moraines, are being now transported by the Alaskan glaciers.

The fossil tree trunks in Arctic coal seams would supply better evidence of a change of climate than the fossil leaves, if there were evidence to prove that the trees had grown in situ. The view that the three months darkness of winter would be fatal to tree growth is now recognised as untenable; but its a fact that forests do not occur north of 70°, although fossil tree trunks have been found beyond that latitude. But these tree trunks were probably carried north as drift wood.

Robert Brown has described the Disco plant beds and come to the definite conclusion that the plants had not grown in situ. Baron von Tol has published photographs of plant beds associated with ancient ice in northern Siberia; but his photographs show the roots of nothing larger than shrubs. In 1896 I had occasion to mine some hundredweights of coal from the seam at Advent Bay, Spitsbergen (lat. 78° 15' N.), and the section exposed gave no evidence that the coal had been formed from vegetation that had grown in situ.

In many places the Arctic shores are white with a litter of pine, fir, and larch logs, which have been floated down the Siberian rivers, drifted across the Arctic Ocean and been thrown upon the shores.[2] These accumulations of drift wood become covered by the growth of moss, saxifrages and Arctic willows; and if then buried beneath sheets of sediment, would form Arctic coal seams, made from timber that had grown in Central Asia.

The palaeobotanical evidence that the Arctic regions had a

1 C. Russell. "Second Expedition to Mount St. Elias." 13th. Ann. Rep. U. S. Geol. Surv., 1893, pl. XIV.

2 A photograph shewing one of these timber strewn beaches has been published in the "Voyage de la Manche," plate V, 1894.

tropical or subtropical climate in the Cretaceous is inadequate; and it is contradicted by the Palaeozoological evidence of the contemporary marine deposits. The Cretaceous marine beds in Greenland have a stunted fauna, which has no tropical or subtropical characters. The British chalk sea was sufficiently cold for drift ice to carry boulders as far south as London and its fauna is decidedly non tropical. The chalk sea was of moderate depth; but its Crinoids were small and scarce; its corals were small and simple; and its mollusca indicate a cooler sea than do the Hippurites, etc., of the Mediterranean beds. In the Lower Cretaceous beds of British Isles, there are abundant shallow sea and shore deposits; but there are no coral reefs, and the general aspect of the fauna indicates a sea decidedly colder than that of the Jurassic. The British Cretaceous marine deposits indicate the prevalence of a cool temperate, and those of Greenland an Arctic climate, in the period when, on the unreliable evidence of fossil leaves, we are asked to believe the conditions in Greenland were tropical or subtropical.

The palaeontological evidence at present available does not throw on us the burden of explaining why the Arctic had a tropical climate, for it simply contradicts assertion as a matter of fact.

IV.—Glaciation due to Local Climatic Variations.

The second line of evidence used to prove intense, widespread climatic changes is the ocurrence of glacial deposits in the temperate zones, and the greater extensions of tropical glaciers. But this evidence has also been used to indicate more extreme changes than are necessary to explain the facts. Thus it appears to be sometimes considered that the glacial beds of South Africa, India and Australia, prove that in one epoch of the Upper Paleozoic the whole area of the Indian Ocean, from 30 N. lat. in India to more than 40° S. in Tasmania was undergoing glaciation.

The difficulty of explaining former glaciations has been greatly increased by such assumptions as that they were due to the development of a severer climate at the same time throughout the world.

There is not yet adequate evidence that the former glaciations were accompanied by a universal change of climate. It is true that there is evidence of a more extensive Pleitocene glaciation in many regions of the world, including Mount Kenya, upon the equator in British East Africa, Mount Kosciusko in Southeastern Australia, western Tasmania, the South Island of New Zealand, Patagonia and a belt practically all across the temperate regions of the Northern Hemisphere. Accordingly it is claimed, as by Ekholm (op. cit. p. 34) that the snow line was everyvhere 1,000 metres lower at the time vhen Europe had its "Great Ice Age." But there are too many cases in which evidence of such former extension has been sought for in vain, for a universal lowering of temperature in the Pleistocene to be accepted as yet finally established. In the North Island of New Zealand, there is no evidence of any former glaciation; and had its existing snowfields extended more than 3,000 feet lower, they should have left some traces of so great growth. D'Orbigny and Whymper both failed to find any evidence of any greater extension of the existing glaciers on the Equatorial Andes, than could be explained by a local variation in the winds; in Equatorial Africa no Pleistocene glacial deposits have been found, except on the dwindling summits of the highest mountains; and the coastal raised beaches give no evidence of any contemporary reduction in the temperature of the adjacent seas. There is no evidence of any Pleistocene glaciation on the mainland of Australia, except on the highest summit of the Australian Alps; and through Mount Kosciusko, which is now 7256 feet above sea level, in a region with a 60 inch rainfall, had once a few small glaciers, there is no evidence in Australia generally of a colder Pleitocene climate. In fact the early Pleistocene or Pliocene fauna of central Australia indicates the extension, then of the tropical fauna of northern Australia into the temperate regions of the Continent. Neither the flora or fauna of the Pleistocene deposits of Victoria indicates a colder climate than that of the present time.

The glaciations themselves, moreover, though often very extensive, appear to have been always local. Thus those of the Pleistocene in the Northern Hemisphere were grouped around

a series of centres, which are not always in particularly high latitudes. In North America there appear to have been three glacial centres, that of the Canadian Rocky Mountains in lat. 55°|60°; that of eastern Canada in lat. 50|55°, and with its southern edge extending to 42° N.; and that of Greenland of which the centre is from 70|75° N.

In Europe, the glaciation of the British Isles, extended as far south as 52°; that of Scandinavia, from a centre between 60° and 65° N., overrode the country as far south as northern Germany in lat. 53°; and the other centres further south developed where high mountains, such as the Alps, occurred near warm seas.

V.—Causes of Climatic Variations.

If it be accepted that former climatic changes involve less extreme changes of temperature than have been generally assumed, and that we are not called on to explain former tropical forests in the Arctic lands, or fossil coral reefs in the Arctic seas, or occasional universal refrigerations of the earth, then the problem of climatic variations is greatly simplified.

1.—The Elevation Theory.

Several explanations, attractive from their simplicity, may then be at once dismissed. The theory of the migrations of the poles into temperate regions, although supported by Oldham and Penck for the Upper Palaeozoic glaciation, is contradicted by the evidence of palaeontology; and the explanations it would give of world wide changes are not required. The once popular theory that ice-caps have been produced by the greater elevation of the land may be abandoned, as opposed to meteorological principles, and as implying a reversal of the facts, glaciations having so often accompanied periods of greater submergence of the land, and milder climates having coincided with periods of emergence; and it would be quite inapplicable to the Upper Palaeozoic glaciation of Australia, of which the glacial deposits were in places submarine.

2.—The Obliquity of the Ecliptic.

Nor, in spite of the fresh use made of it by Ekholm and Dickson, does the variation in the obliquity of the ecliptic appear to help materially; for all the influences of this agency are open to the fundamental objection that variations in obliquity recur at what, geologically speaking, are short and frequent intervals; whereas ancient glaciations happened but seldom, and were apparently irregular in their time of return.

3.—Variations in the Carbonic Acid Content of the Atmosphere.

The view that now seems most popular explains the major climatic changes by variations in the powers of selective absorption of heat by the atmosphere. The change is attributed either to variations in the amount of aqueous vapour as urged by de Marchi,[1] or of carbon dioxide as advocated by Svante Arrhenius,[2] and recommended to us by the brilliant advocacy and high authority of Prof. T. C. Chamberlin.[3]

The aqueous vapour theory has been adequately disposed of by Arrhenius, whose alternative is especially attractive, as it demands comparatively small differences of temperature and very modest variations in the amount of carbonic acid. Thus he calculates that an increase of the carbonic acid from .03 to .09% would give the Polar regions a temperate climate, by a rise of from 12° to 16° F. Nevertheless, this theory—that former colder periods were due to a reduction of the carbonic acid in the air and warm periods to an increase in its amount—is faced by objections which I venture to think still inadequately answered.

No one is likely to deny the possibility of great variations in the former composition of our atmosphere. The theories of Ko-

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1 De Marchi. "Le Cause dell'era Glaciale." Pavia, 1895.

2 S. Arrhenius. "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground." Phil. Mag. Ser. 5, vol. XLI, 1896, pp. 237-276.

3 C. Chamberlin. "A Group of Hypotheses bearing on Climatic Changes." Journ. Geol. Vol. V, 1897, pp. 676-683. "The Influence of Great Epochs of Limestone Formation upon the Constitution of the Atmosphere." Ibid. Vol. VI, 1898, pp. 609-621.

ene (1856), Phipson (1893-4), or Stevenson (1902)[1] that the primaveral atmosphere was many times larger than at present, was rich in carbonic acid, and had no free oxygen, may be inapplicable to any part of geological time; though they may very likely be true for the first formed atmosphere, long before the date of the oldest known sedimentary rocks. From the earth's surface we look up through zones of atmosphere, in which the oxygen and carbonic acid steadily diminish, and the minute proportion of hydrogen at sea level increases, until, 50 miles high, the air consists practically of hydrogen alone.[2] The aurora flares above us in a mixture of hydrogen and neon; and as there is evidence of such fundamental variations in the atmosphere in space, there may well have been marked changes in time. There are so many agents pouring carbonic acid into the air, and so many others withdrawing it, that it would be strange if the present equilibrium had always been maintained.

(a) *The Oceanic Control.*

Nevertheless it must not be forgotten that the ocean, as shewn by Schloesing,[3] supported by the weighty experiments of Dittmar, controls the amount of carbonic acid in the atmosphere. If the amount of carbonic acid in the atmosphere is diminished, the bi-carbonates in the sea are dissociated; the gas thus liberated is poured into the air, until the former equilibrium between the tension of the carbonic acid in the atmosphere and in the sea is reestablished. Hence a reduction of carbonic acid in the air is automatically followed by the discharge of nearly as large a quantity from the sea; so that any reduction is distributed between the air and the ocean. Any increase of carbonic acid in the atmosphere is followed by the reverse change, and only one sixth of the amount poured into the atmosphere is retained there. It is true that great variations in the relative

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1 J. Stevenson. "The Chemical and Geological History of the Atmosphere." Phil. Mag. ser. 5, Vol. L. pp. 312-323, 399-407. Also Pt. II, "The Composition and Extent of the Atmosphere in very Primitive Times." Phil. Mag., Ser. 6, Vol. IV, 1902, pp. 448-451.

2 Sir J. D. Dewar. "The Problems of the Atmosphere." Proc. R. Inst. Vol. XVII, 1902, p. 226.

3 Schloesing. "Sur la Constance de la Proportion d'acide carbonique dans l'air." Compt. Rend., Vol. 90, 1880, p. 140.

extent of sea and land would affect the dissociation pressure of the bi-carbonates in the sea; but it would require a great reduction in the area of sea surface to affect the equilibrium appreciably.

(b) *Possible Evidence from Palaeontology.*

Efforts may be made to ascertain from palaeontological evidence whether the atmosphere has recently altered its composition. This line of enquiry does not promise reliable conclusions, owing to the powers of adaptation of both animals and plants to changes in the atmosphere. An increase in carbonic acid, provided it be not accompanied by organic pollution, from three parts to 100 parts in 10,000—an increase ten times as great as the maximum considered by Arrhenius—is inappreciable to man. The ordinary data of mine ventilation and the experimental results of Dr. J. S. Haldane and Dr. Lorraine Smith, shew that men can stand, whithout serious inconvenience, an increase of carbonic acid to even 400 parts in the 10,000; and as there is no probability of temporary variations to any such degree, a slow increase in the carbonic acid contents of the air would probably have a greater indirect effect upon animals through its action on the temperature, than by its direct effect on respiration.

(c) *Non-Coincidence of Dates.*

The main objection no the atmospheric variation theory is that it does not explain the facts of historical geology. And geologists, as the historians of the earth, test theories whenever possible, by their agreement with contemporary records.

The influence of variations of the carbonic acid contents of the atmosphere on temperature should affect the whole world simultaneously.[1] The change need not be the same in all latitudes, as is shown by Arrhenius' tables; and also by the variation in the proportion of carbonic acid with latitude, which is rendered probable by the evidence adduced by Letts and Blake.[2]

1 It is sure that according to the results of Muntz and Aubin there is at present a difference in the amounts of Carbonic acid in the air of the northern and southern hemispheres; they estimate the mean amount as .028% in the northern and .027% in the southern. This difference follows from the greater area of sea in the southern hemisphere, which can hardly have been much greater at any previous period.

2 E. A. Letts and R. F. Blake. "The Carbonic Anhydride of the Atmosphere." Sci. Proc. R. Dublin, Soc. Vol. IX, 1900, pp. 179-180.

Nevertheless it might be expected that corresponding positions in the two hemispheres should be almost equally affected.

There is however no evidence of a glaciation in Europe[1] in Upper Carboniferous or Permian times corresponding to that of South Africa or Australia—in spite of the unusually extensive knowledge of the land conditions of that period. The Indian Glaciation of Pokaran in lat. 25° N., of Chanda in lat. 19° N. may correspond to that of South Africa from lat. 24° S. to 34° S., or of southeastern Australia from 30° S. to 40° S. But the general collapse of the supposed Permian glacial conglomerates of the English Midlands, and the unconvincing evidence collected to support Carboniferous glaciation in France, as by Julien,[2] leaves us with no evidence of any refrigeration of Europe at the date of the Gondwanaland glaciation.

Again the Upper Palaeozoic glacial deposits of south-eastern Australia do not appear to have been synchronous in all the localities. The glacial deposits on the northern coast of Tasmania have been shown by Kitson[3] to be of the age of the Mersey Coal Measures of Tasmania, which may be correlated with Lower or Greta Coal Measures of New South Wales. The Victorian glacial deposits are probably on approximately the same horizon, which agrees with some of those of New South Wales. But according to David,[4] there were glacial deposits in New South Wales at the following different stages in the Permo-Carboniferous.

Branxton Glacial beds in the Upper Marine Series.

Greta Coal Measures.

Shales with occasional erratics in the Lower Marine Series.

Lochinvar Glacial Beds at the Base of the Lower Marine Series.

Again, whatever view may be held on the controversy as to the occurrence of warm interglacial periods during the Pleis-

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1 There is some evidence of glacial beds of this period on the east of the Ural Mountains.

2 A. Julien. "Anciens glaciers de la Période Houillère dans le Plateau Central de la France." Ann. Club Alpin Français, Vol. XXI, 1894, pp. 28.

3 A. E. Kitson. "On the Occurrence of Glacial Beds at Wynyard, near Table Cape, Tasmania." Proc. R. Soc. Victoria, new Ser., Vol. XV, 1902, p. 34.

4 T. W. E. David. "Discoverey of Glaciated Boulders at Base of Permo-Carboniferous System, Lochinvar, New South Wales." Journ. R. Soc. N. S. Wales. Vol. XXXIII, 1899, pp. 154-159.

tocene glaciation of Europe, it will be generally admitted that considerable oscillations occurred in the extent of the ice. Thus the evidence in the British Isles, strongly supports the view that after the maximum glaciation, there was a reduction in the extent of the ice, and then after some interval, a fresh advance of valley glaciers. And such interludes, of which in the British Isles there may have been more than one, would appear to require considerable variations in the amount of carbonic acid in the atmosphere, repeated within a short period of time.

Weighty evidence is also given against Arrhenius' theory by the dates of the glaciations, as they do not correspond with those at which variations in the carbonic acid contents of the atmosphere, would be most probable. Wide spread volcanic eruptions offer the simplest explanation of the addition of large volumes of carbonic acid to the atmosphere; but periods of intense volcanic activity do not appear to have been always followed by glacial epochs.

The great volcanic periods—the Devonian, the Permian, the Upper Cretaceous, the Eocene and the Oligocene,—were not followed by marked developments of glaciers. The one coincidence is in the case of the Upper Carboniferous or Permian glaciation of Gondwanaland. The Pleistocene glaciation followed a period in which volcanic action was powerful, but was probably less than at other periods not followed by glacial advance.

Again with the reverse case. Periods of especially active consumption of Carbonic Acid were not followed by glacial epochs. As Professor Chamberlain has shown the most extensive removal of Carbonic Acid from the atmosphere was probably during the formation of sheets of limestone; while coal seams contain a smaller, but still large amount of Carbon obtained from the carbonic acid of the air. The great limestone building periods fixed enormous quantities of carbonic acid, which must have come from the atmosphere, because, if obtained from the sea, its fixation must have led to the transference of a fresh supply from the atmosphere. The greatest limestone periods are probably the Lower Carboniferous, the Jurassic, the Upper Cretaceous and the Eocene and the Miocene. But none of them was

a period of active glaciation. Speaking generally, they appear to have been warmer, than the average. Thus in the British Isles we find unusually well developed growths of corals in the Lower Carboniferous and the Jurassic; the British Eocene flora included plants suggestive of a warmer climate than that of the present time, while the marine faunas of the Middle Cainozoic in Europe and southern Australia, indicated that those seas were then warmer than they are to-day. The Upper Cretaceous alone gives any indications of cold conditions, as shown by the probably ice-borne boulders in the English chalk, and the temperate aspect of ist fauna; but the oft stated view that Greenland then enjoyed a subtropical climate rests on evidence, which at least does not support the idea that the period was one of universal severity. The apparent independence of the times of limestone formation and glaciation is further shown by the face that the chief glacial periods—the Cambrian in Australia and eastern Asia, the Upper Carboniferous or Permian of South Africa, India and Australia, and the Pleistocene in the Northern Hemisphere were not periods of great limestone formation.

4.—Changes in Temperature Gradient of the Atmosphere.

The influence of changes in the composition of the atmosphere is also the basis of Dickson's theory.[1] But he traces its influence, not through the variations in heat absorption by the atmosphere, but through variations in the temperature gradient from the tropics to the polar regions. Dickson's paper is of value from its clear statement of the facts showing that a development of glaciation is possible with only a small change in mean temperature.

Dickson appeals to a former difference in the temperature gradient between the polar and equatorial regions; he attributes the change in gradient either to the changes that are always in progress in the obliquity of the ecliptic, or to variations in the carbonic acid in the air. He shows that either would give

1 H. N. Dickson. "The Mean Temperature of the Atmosphere and the Causes of Glacial Periods." Geogr. Journ., Vol. XVIII, 1901, pp. 516-523.

effects of the magnitude required; but it seems doubtful whether either will agree whit the records of historical geology; for as regards the first cause, the change in the obliquity is geologically speaking a short and cosntant oscillation; and as to the second, as it rests on the variation of carbonic acid, it is open to the same objetions as to those of Arrhenius' theory.

5.—Changes in Atmospheric Circulation.

That the explanation of glacial periods is to be sought in changes in the circulation of the atmosphere resulting from geographical changes, has been several times suggested, in accordance with Buchan's results.[1] This principle has received ist fullest application to a specific case by Harmer[2] to the Pleistocene climate of north-western Europe. And moreover Dickson has shown how the distribution of the glaciations in that case corresponds whith what would be expected, if they were due to differences in atmospheric circulation. Such meteorological changes would be quite inadequate to explain the occurrence of a tropical climate in the Arctic regions, but they would account for changes of temperature of a few degrees, and for glaciations by local concentrations of the snow-fall. The difference between the climates of western Europe and eastern America is obviously due to meteorological conditions, resulting from geographical position. The differences on the two coasts of the North Atlantic were naturally first atributed to the influence of ocean currents; but with our present knowledge as to their feebleness and the ending of the Gulf Stream of Newfoundland, ocean currents may be dismissed as a very subordinate factor. A different distribution in air pressure resulting is a different circulation of the wind would probably be a more effective cause, and appear to me at present to offer the best prospects of a satisfactory solution to the problem. It is the only explanation that seems to agree with the essential facts,

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1 For instance, I endeavoured to show in 1894, that the more extensive glaciation of Mount Kenya was due to a local difference in the atmospheric pressure due to the former greater height of this denuded volcano. "The Glacial Geology of Mount Kenya." Quart. Journ. Geo. Soc. Vol. L, 1894, pp. 527-530.

2 F. W. Harmer. Quart. Journ. Geol. Soc., Vol. LVII, pp. 405-472.

viz, the development of glaciation from scattered centres, and at somewhat different dates, and the apparent independance of the glaciations in distant continents, and their apparent direct dependance on a particular adjustment of meteorological conditions.

The slow march of glaciation across North America and possible also across Europe, is intelligible on this hypothesis, and there is no reason, on that theory, to expect coincidence of glaciations in the northern and southern hemispheres. The former glacial extensions in Australasia can thus be easily explained; for the evidence, so far, appears to be only convincing in localities either on the edge of the Antarctic regions, or in local areas where the meteorological conditions are unusual. New Zealand is often quoted as having been glaciated, either in the Pleistocene, or at the same time as the glaciation of Europe. But it should be remembered that there is no evidence yet of any glaciation in the North Island of New Zealand, and the former range of the glaciers in the South Island has been considerably exaggerated. On the western slope of the South Island, glaciers in lat. 43°20' S. still come down to the level of 600 feet above the sea; and it is along that coast with its intense rain-fall, that the former ice extension is most cleary shown. In Tasmania the Pleistocene glaciation resulted from a heavy snowfall along the western edge of the Central Plateau, and the low moraines yet proved, occur only in the valleys leading down to the western coasts; but on the mainland of Australia, the evidence of former glaciation is very scanty. Its existence has been finally established by the work of David and Pittman, on Kosciusko; but the numerous cases of Pleistocene glaciation that have been asserted in Victoria cannot be maintained. I have visited all but two, and saw no evidence of glacial action in any of them; and the evidence relied on in both the places I have not seen, has been described by others as explicable by non-glacial agencies.

The Permian or Carboniferous glaciations of South Africa India and Australia being in low latitudes and ranging down to sea level in New South Wales and in the Salt Range appears at first sigth to be the most difficult problem in palaeome-

teorology. But the question is simplified by the following considerations.

1.—The geographical conditions of the areas concerned were very different from those of the present day.

2.—The three best known glacial centres occurred on the borders of the old continent of Gondwanaland, farthest from the equator; and they were probably all near mountainous country, facing seas open to the colder zones.

3.—The only cases where the glacial deposits reached the sea, were in the areas furthest from the tropics, and probably most exposed to cold Winds.

4.—Icebergs occasionally now reach almost to the tropics; thus in April, 1894, one was seen in the South Atlantic in lat. 26°30' S.

5.—The glacial deposits appear to have been absent from the more tropical parts of Gondwanaland, as they disappear towards the north in both Australia and in South Africa.

Both in Australia and South Africa the glaciation ocurred in areas where mountains existed near the sea. In southeastern Australia there is ample evidence that a wide Upper Palaezoic sea lay to the east and a gulf to the north-west of Australia. In all probability there was a large extent of land stretching southward and cutting off the cold southern ocean from the seas, which extended south-ward from the tropics. Under such conditions the wind systems would have traversed the Australian lands upon a different path from that which they follow now, and they would not have advanced so steadily. The winds would have carried large quantities of moisture southward from the warm northern seas, and it would have been precipitated on the mountains of that period, which were kept cold by southerly winds, chilled by their passage over the former extension of Australia to the south. In South Africa and in South America the question is simpler, as there is no proof of the glacial deposits having been laid down at sea level; they may have been formed upon the flanks of mountain areas, kept abundantly supplied with snow, by west winds blowing in from the adjacent oceans. In India, the conditions were probably meteorologically similar, the glaciation having been on the cooler edge of Gond-

wanaland, where it was bounded by a temperate sea; and through the glaciers ranged into the tropics in Southern India as far south as 17°20' N. lat. there is no proof that they occurred there at low levels.

It appears, therefore, probable that variations in climate, which have been established on adequate evidence, can be accounted for by differences in atmospheric circulation, due to different distributions of land and water. All the evidence available regarding the Upper Palaeozoic glaciation of Gondwanaland appears to be consistent with the view that the glaciers developed, like those of the Pleistocene glaciation of North America and of north-western Europe, in a number of scattered localities, where mountains occurred beside the sea, and where the meteorological produced a high snowfall and a low summer temperature.